UDC 621.397:
621.377

1969
THE QUEEN'S AWARD
TO INDUSTRY

BBC

RESEARCH DEPARTMENT

REPORT

Possible techniques for the recording of digital television signals

No. 1969/42

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

POSSIBLE TECHNIQUES FOR THE RECORDING OF DIGITAL TELEVISION SIGNALS

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It uses SI units in accordance with B.S. document PD 5686.

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POSSIBLE TECHNIQUES FOR THE RECORDING OF DIGITAL TELEVISION SIGNALS

DIGITAL RECORDING SUMMARY CHART

Recording Technique	Recording Speed bits/sec.	Replaying Speed bits/sec.	Bit Error Rate	Packing Density bits/sq.cm.	Erasability	Processing Time
I Magnetic Tape Recording a) Static Head Longitudinal Recording	2×10^6 70×10^6 *	2×10^6 70×10^6 *	1 in 10^7 1 in 10^8 *	$4{\cdot}5 \times 10^3$ $1{\cdot}6 \times 10^5$ *	Yes	None
b) Transverse-scan Recording	10^7 10^8 *	10^7 10^8 *	1 in 10^9	2×10^4	Yes	None
II Magnetic Disc Stores a) Exchangeable Discs with Flying Heads	10^6	10^6	1 in 10^7	6×10^3 Total Storage up to 10^8 bits per disc pack	Yes	None
b) Fixed Discs with Flying Heads	3×10^6	3×10^6	1 in 10^7	6×10^3 Total Storage up to 4×10^9 bits per disc pack	Yes	None
c) Fixed Discs with Heads in Contact	10^7 *	10^7 *	1 in 10^7 *	5×10^5 * Total Storage approximately 2×10^9 bits per disc pack	Yes	None
III Magnetic Drum Stores	3×10^6	3×10^6	1 in 10^7	Total Storage of approx. 4×10^7 bits	Yes	None
IV Electron-beam Recording a) Conventional Photographic Film	6×10^7 10^8 *	10^7 10^8 *	Not Known	10^5 bits 3×10^6 *	No	30 secs.
b) Replaying of Scintillator-coated Photographic Film		10^7 10^8 *	Not Known			
c) Thermoplastic Film	5×10^7 10^8 *	5×10^7 10^8 *	Not Known	2×10^5	Yes	None
V Laser-Beam Recording a) Photographic Film	10^8	10^8	Not Known	10^5 $3{\cdot}1 \times 10^6$ *	No	30 secs.
b) Punched Tape	2×10^7 10^8 *	2×10^7 10^8 *	1 in 10^9	10^8 *	No	None
c) Photochromic Recording	10^8 *	10^8 *	Not Known	10^6	Yes	None
d) Thermo-magnetic Recording/ Magneto-optic Replaying	10^6 10^7 *	10^8 *	Not Known	10^6 $1{\cdot}55 \times 10^7$ *	Yes	None
VI Electron-beam Recording with Laser-beam Replaying using Optical Spatial Filtering	10^7 *	10^8 *	1 in 10^7 * to 1 in 10^9 *	$9{\cdot}2 \times 10^4$ $3{\cdot}1 \times 10^6$ *	No	30 secs.

* Potential performance figures

October 1969

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POSSIBLE TECHNIQUES FOR THE RECORDING OF DIGITAL TELEVISION SIGNALS

SUMMARY

The salient features of various techniques potentially suitable for the recording of digital television signals are compared. It is concluded that digital recording of a few television fields is practicable now and that digital recording of programmes for broadcasting could probably be developed within five years. This latter requirement demands further improvements in reading and writing speeds of the recorder, coupled with an increase in the information packing density on some recording media.

1. INTRODUCTION

The conversion of analogue television signals to digital form[1,10,11,12] has several practical advantages for transmission and programme operations.[2,3] Regeneration of digital signals can be carried out reliably and digital television recordings can consequently be copied with negligible error through far more generations than is attainable with analogue recordings. The additional bandwidth required of transmission and recording channels for digital television signals is exchanged for a substantial reduction in the required signal-to-noise ratio for a given subjective level of picture impairment. In addition to recording, the availability of television signals in digital form facilitates the application of digital computer techniques to operations such as programme editing, signal switching and signal processing.

Sampling theory[5] and experiment[2] both indicate that, for quantizing television signals of bandwidth 5·5 MHz and converting them to digital form, a sampling rate of about $1{\cdot}3 \times 10^7$ samples per second is required. It is likely that 8 bits per sample will be needed for high-quality television pictures, and this figure will be assumed here. Consequently the data transfer rate to be considered is 104 megabits per second.

The report provides brief descriptions of several techniques for high-density digital recording, and compares their potential for development and application to digital television recording.

2. TECHNIQUES FOR DIGITAL RECORDING ON MOVING MEDIA

This section has been sub-divided in order to describe magnetic, electric, optical and hybrid recording techniques. There is naturally a good deal of information common to all the techniques, especially in the problem of signal coding. Not all the techniques described have yet been used for digital recording. However, they are all potentially suitable for it, but not necessarily at speeds and information densities high enough for television.

2.1. Magnetic Recording

2.1.1. Magnetic Tape Recording

Static Head Longitudinal Recording

Longitudinal magnetic recorders used for recording digital signals usually comprise 7 or 9 heads, with magnetic gaps 2 microns or more in width, accurately stacked in parallel across, and in contact with, 12·7 mm wide tape. The rate at which head channels are capable of transferring digital data to and from the tape at a given error rate varies considerably according to the magnetic, geometric and dynamic properties of the tape and recorder being used, and the digit coding system used to detect errors. The data transfer rate normally encountered on currently available recorders in this class is about 2 megabits per second, distributed among the parallel magnetic heads, at an overall error rate of 1 bit in 10^7, and a packing density of $4{\cdot}5 \times 10^3$ bits/sq.cm. On 12·7 mm wide tape, the corresponding tape speed is about 3·5 metres per second. The normal useful life of the tape is about 10^5 passes.

Digital data to be recorded is almost invariably expressed in binary digits. These digits are usually encoded in each channel so that the tape is always magnetized to saturation in one or other of two possible polarizations. In one form of polar baseband code, the polarization is changed whenever a binary symbol '1' is to be recorded. This code is known as 'non-return to zero, 1 (or 'mark')', or NRZ1 in abbreviated form; its waveform is illustrated in Fig. 1(*a*). One of the recorded tracks is normally reserved for a bit which makes odd the number of binary 'ones' in each row across the tape. This facilitates a simple form of error detection where the odd parity can be checked.

The NRZ1 code, coupled with saturation-magnetization recording, is widely used, and is satisfactory provided that not more than about 40 bits per millimetre are packed on to each tape track. At higher packing densities, dynamic instabilities of the tape transport, and misalignment of stacked heads begin to cause timing errors in the recorded data when it is replayed; it becomes difficult to synchronize the operation of equipment with data received from

the tape. It therefore becomes desirable to use 'self-clocking' codes, such as the 'NRZ frequency doubling' code shown in Fig. 1(*b*). Here the polarization changes at every transition between symbol intervals, and if the symbol is a '1', a further change occurs at the sampling instant, which is in the middle of the symbol interval. The NRZ frequency doubling code is also known as the 'split phase mark' or 'SφM' code.

Other limiting factors, involving the tape coating, the head-gap geometry and the effective head-to-tape spacing become more prominent as the recorded bit density is increased,[13] and the recording technique has to be made correspondingly more sophisticated to combat the associated rise in error rate and to facilitate error detection and correction.[4]

There is a limit to the minimum length of tape coating which can be used to record a flux reversal from one polarization of saturation magnetization to the other. The flux reversal cannot effectively be made more sharply than that which would set up a self-demagnetizing field equal to the coercivity of the tape coating. For most tapes in use today with high density recorders the limit falls at a linear packing density of about 60 bits per millimetre.[14] This limit can be circumvented without recourse to special tapes by magnetizing the tape to a point below saturation, thus permitting narrower spacing of flux reversals before the self-demagnetizing field reaches the value of coercivity. The effective signal-to-noise ratio is reduced and therefore the bit error rate rises, but the use of improved data checking can outweigh this disadvantage. For example, a successful non-saturation digital recording technique has been reported which uses a.c. bias and the NRZ frequency doubling code, and which attains a linear packing density of 240 bits per millimetre at an error rate of 1 bit in 10^8. The magnetic gap in the recording head is about 2 microns, and that in the reading head is about half a micron. The input data is in the NRZC code where, as depicted in Fig. 2(*a*), the signal polarization is reversed only when the digit changes from '1' to '0' or *vice-versa*. (The 'C' in NRZC denotes 'change'.) In order to reduce digit errors during the record/replay process, the NRZC input data undergoes NRZ frequency-doubling encoding before it is recorded on the magnetic tape. (The waveforms in Figs. 2(*a*) to 2(*e*) illustrate the sequence of signal processing which takes place.) When replaying from the tape, two versions of the recorded data are generated for checking purposes; one is undelayed (Fig. 2(*b*)), and the other is delayed by one symbol interval (Fig. 2(*c*)). These two waveforms are compared in a coincidence gate which yields a '1' only when the inputs to it are identical (Fig. 2(*d*)). The timing error shown at the end of the third symbol interval of the coded waveform is corrected by filtering out the subsequent erroneous spike in the output from the coincidence gate (Fig. 2(*e*)), which is the same as Fig. 2(*a*), the true data, delayed by half a symbol interval. If there are any spurious transitions or 'dropouts' of recorded information on the tape, they could manifest themselves as transitions during a symbol interval in the output waveform, (Fig. 2(*e*)). These transitions are not compatible with the NRZC code and are therefore easily identified and suitable compensation can be applied.

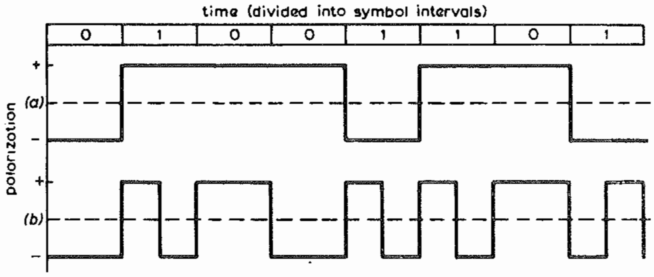

Fig. 1 - Examples of coding used to record binary data on magnetic tape

(*a*) 'Non-return to zero, 1' waveform

(*b*) 'Non-return to zero, frequency doubling' waveform

The practicable limits on linear packing density and parallel-track density currently attained by research and development workers, appear to be about 400 bits per millimetre[13] and four tracks per millimetre[16,17] respectively, with a corresponding error rate of about 1 bit in 10^7. The practical limit on tape width, governed chiefly by problems associated with tape transport and the precision of stacked heads, is about 25 millimetres. Using these figures we find the corresponding values of surface packing density and tape speed to be $1{\cdot}6 \times 10^5$ bits/sq.cm. and 3 metres per second respectively for the digital television data rate of 10^8 bits per second.

Transverse-scan Recording

Signal transduction on transverse-scan magnetic recorders for digital signals is usually effected by four or eight heads mounted on a headwheel about 50 mm in diameter.

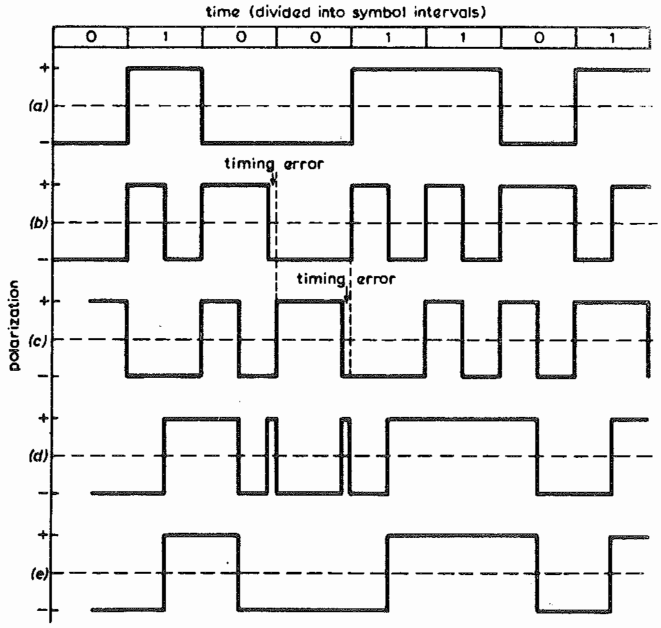

Fig. 2 - A technique used to reduce data errors in a record/replay system

(*a*) 'Non-return to zero, change' waveform

(*b*) 'Non-return to zero, frequency doubling' waveform

(*c*) As (*b*) but delayed by one bit interval

(*d*) Output from coincidence gate fed with (*b*) and (*c*)

(*e*) As (*d*) but after low-pass filter and clipper

The tape used is 50 mm wide with transversely orientated magnetic particles, and is transported past a guide in such a way that the heads sweep across the tape. The heads deflect the tape by about 50 microns into a groove in the guide. Each head has a magnetic gap of between one and two microns and traverses the tape in about one millisecond, resulting in a relative head-to-tape speed of about 40 metres per second, and a maximum data transfer rate of around 10 megabits per second. The 'penetration' of the heads into the tape results in a relatively low signal transfer loss due to the head-to-tape spacing, and, as a consequence, error rates as low as 1 bit in 10^9 are achieved when spatial data redundancy and suitable error-reducing codes are used. Unfortunately, the high stresses induced in the pole-tips of the heads and in the tape limit the useful pole-tip life to a few hundred hours and the useful tape life to a few hundred passes. A maximum information packing density of about 2×10^4 bits/sq.cm. is attained by transporting the tape at about 60 centimetres per second past a headwheel with eight heads.

By exploiting the full data handling capacity of the recording head (thereby avoiding the data redundancy required to effect error protection), a significant increase in the data transfer rates can be attained. With no error protection on an eight head machine it would be possible to achieve data transfer rates approaching 10^8 bits per second by increasing the tape speed to about 1·1 metres per second.

2.1.2. Magnetic Disc Stores

The need for peripheral storage of computer data with higher capacity, data transfer rates, and reliability, has led to the development of digital magnetic recorder stores which use metallic discs, coated with a thin layer of magnetic material which acts as the storage medium. Some stores have fixed discs, others have exchangeable discs. Further, some fixed-disc stores have magnetic heads which are held in contact with the recording surface, but at the moment, most disc stores have 'flying-heads' which are held just out of contact.

Exchangeable Discs with Flying Heads

Exchangeable discs have diameters of about 350 millimetres and are usually stacked on a common axis in packs of up to six. The spacing between the individual discs is sufficient to allow the reading and writing head assemblies to traverse the recording tracks, as depicted in Fig. 3. The individual head assemblies are normally ganged together to form a single comb-like head-assembly, and are usually moved across the tracks by a stepping actuator. The actuator is capable of completing the movement between adjacent tracks in upwards of 25 milliseconds, and between the most widely separated tracks in about 150 milliseconds. Track densities of about four per millimetre are common, the corresponding number of tracks per disc surface being about 200. The data transfer rate to and from a given track is about 10^6 bits per second, the corresponding storage density being about 3×10^4 bits per track (about 40 bits per millimetre), or 6×10^7 bits per pack of ten disc surfaces (about 6×10^3 bits per sq. cm.). There is usually only one effective data transfer channel per disc surface, comprising one reading and one writing head, or one combined reading and writing (read/write) head. However, some exchangeable disc stores have as many as 12 read/write heads per surface which are used sequentially. Provision is normally made to read or write on only one head at a time. On almost all present-day exchangeable-disc stores the heads are spaced from the recording surface by between one and five microns, approximately 10% of the recorded bit length. The heads are profiled in such a way that they 'fly' in stable equilibrium by virtue of a venturi effect, under the action of forces due to gravity, atmospheric pressure, aerodynamic drag and boundary-layer effects, and also to the sub-atmospheric pressure of the air flowing spirally outwards across the disc as a result of its rotation.[18] An additional force of a few grams weight acts on the heads by way of a spring finger which holds them against the disc surface when the latter is stationary. The magnetic disc coating is usually composed of iron oxides. However, cobalt, nickel, and phosphorus, deposited by electroplating or ion-exchange processes, are also used to produce discs having a relatively thin coating (25 to 5000 nanometres), of high durability and smoothness.[19] Relatively high ratios of coercivity to remanent intensity of magnetization are achieved with metallic coatings, and thereby unwanted effects such as self-demagnetization and interference between adjacent bits are reduced.[6]

Fixed Discs with Flying Heads

The storage properties of fixed-disc stores differ from those of exchangeable-disc stores chiefly because, with the fixed mounting, larger and more numerous discs can be combined into a single storage unit.[20] Data transfer rates, information packing densities, and data-access times, are generally of the same order as those of exchangeable-disc stores, (at least one device can transfer data at 10 megabits per second). However, fixed-disc stores can provide storage capacities up to about 3×10^9 bits. Both oxide and metal coated discs are again used, and the dynamic properties of heads and discs are similar to those of exchangeable-disc stores. A few special-purpose stores are available, including a single-disc seven megabit store, comprising up to 72 channels which are simultaneously operable each at transfer rates of up to 3 megabits per second.

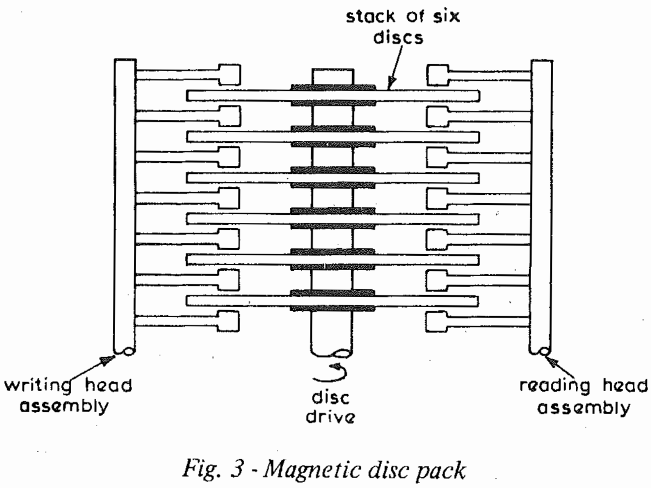

Fig. 3 - Magnetic disc pack

Fixed Discs with Heads in Contact

Disc stores operating with the magnetic heads in contact with the disc are a relatively new development which has become practicable because of improvements in disc and head materials. Hitherto it has not been possible with in-contact devices to attain adequate head and disc lives at the requisite head-to-disc speeds of 25 or more metres per second. Cobalt-nickel and cobalt-nickel-phosphorus coated discs, usually protected by a thin surface layer of rhodium or ruthenium, have been available for a few years with very smooth surface finishes, but only recently has it become practicable to match their high-quality finish with ferrite heads. These heads are often monocrystalline in order to keep the wear rate down to an acceptable level on both discs and heads. Surface roughness of less than 25 nanometres (centre-line average)* are now attainable on the contacting surfaces, yielding head lives of at least 500 hours and indefinite disc lives. Data transfer rates and information storage densities are about ten times higher than those attained with flying-head disc stores; they are about 10^7 bits per second and 5×10^5 bits per sq. cm. respectively. Fixed-disc stores having such capabilities plus adequate reliability are not yet at the stage of widespread production, and exchangeable-disc stores with in-contact heads are one stage further removed from availability.

2.1.3. Magnetic Drum Stores

The relatively low access time of digital data when recorded on magnetic drum stores is valued by computer designers. The basic components of such a store are a non-magnetic cylindrical drum, up to about 500 millimetres in diameter and length, externally coated with iron oxide, together with banks of magnetic heads mounted around the outside of the drum. There are several hundred reading or writing heads, one per circumferential track, but for computer purposes only a few are used simultaneously. Magnetic drums are made to rotate at about twice the speed of discs, so that one revolution is completed in as little as 15 milliseconds. Access time is thereby reduced, and the data transfer rate of 2 or 3 megabits per second is about twice as high as that of exchangeable disc stores with flying heads. The total storage capacity of 30 or 40 megabits is lower than that of disc stores. The heads are either mechanically adjusted in banks to run just clear of the drum surface, or they can be arranged to 'fly' in the same way as those on disc stores.

2.2. Electron-beam Recording

The recording of information by scanning certain media with an electron beam is a much more recent innovation than magnetic recording. Consequently, practical experience in this field has been limited, particularly in digital applications and outside the military field. The following descriptions are therefore somewhat lacking in detailed comment on such system parameters as error rate and reliability.

* The arithmetical average of undulations above and below a reference datum in the surface profile. VIZ. B.S.1134.

2.2.1. Electron-beam Recording on Conventional Photographic Film

A beam of energetic electrons striking the emulsion of a conventional photographic film will induce a latent image on the film which is later processed to form a normal image made up of variations in optical density.[21] Optimum exposure of the emulsion requires about 10^8 electrons per square millimetre at energies of about 20keV. Effective beam (spot) diameters of about 10 microns, scanning at normal television rates, with beam currents of about 100 nanoamps at the film plane, have yielded a 50% modulation transfer at about 50 cycles per millimetre on conventional 16 mm photographic film.[22,23] This corresponds to a bandwidth of approximately 10 MHz. The use of a special high-resolution emulsion has yielded experimental results of around 300 cycles per millimetre corresponding to a 60 MHz bandwidth in the 16 mm television film format.[21]

A schematic diagram of an electron-beam recorder designed to record television on photographic film is shown in Fig. 4. The film forms the boundary between the film chamber, held at low vacuum by a rotary pump, and the scanning tube held at high vacuum by a diffusion pump. The secondary emission pick-up from the film permits monitoring of the recorded signal, albeit with low signal-to-noise ratio, because the secondary-emission current is directly related to the absorption of primary electrons by the emulsion, i.e. to the recorded signal. In the case of direct television recording the electron beam is deflected into the Faraday cage during blanking. This beam monitoring allows the application of servo-control to the mean film exposure. The mean beam current is controlled by the cathode potential, and the beam is modulated by the signal applied to the grid of the electron gun. Provided that the normal moisture content of the film is preserved,* no increased beam scattering due to the build-up of negative charge on the film is experienced. Recordings intended for conventional optical projection or television are made with high-frequency spot-wobble. Proven means of following, during replay, straight recorded tracks on ordinary photographic film with an electron beam do not appear to have been described in the literature. However, secondary emission techniques similar to those to be described in Sections 2.2.2 and 2.2.3, may be applicable.

2.2.2. Electron-beam Replaying of Scintillator-coated Photographic Film

Replaying of photographic film by direct electron-beam scanning requires a means for electron-to-photon conversion so that the variation of optical density on the film can be sensed by a photomultiplier placed behind it. A technique has been developed which utilizes ordinary photographic emulsions coated (before or after exposure) with a thin, transparent plastic scintillator,** one or two microns thick. The scintillator has extremely low granularity and

* Drying out of the film in the vacuum has not been found to be troublesome, presumably because of a low pumping speed for water vapour.

** The scintillator is a phosphor which emits a flash of light when excited by an incident electron beam.

afterglow time (about 2 nanoseconds). The basic form of the equipment is similar to that of the electron-beam recorder illustrated in Fig. 4, with the addition of a light guide located immediately behind the film which transmits light to the faceplate of a photomultiplier. The scintillator itself is usually coated with a transparent layer of aluminium in order to prevent a build-up of negative charge which could cause patterning and distortion. The beam energy is about 10keV, the beam (spot) size is about 10 microns, and 50% modulation transfer is achieved at about 50 cycles per millimetre. This corresponds to a 10 MHz bandwidth using television scanning rates on 16 mm film. Unfortunately the quantum efficiency of the scintillator diminishes with electronic exposure so that its life is limited to about 1000 scans, thus precluding stop-motion replays.[25]

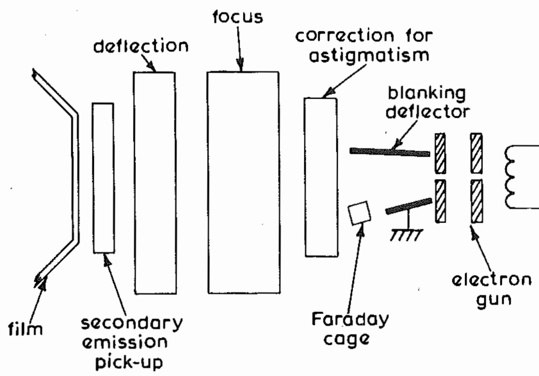

Fig. 4 - Electron-beam television recorder

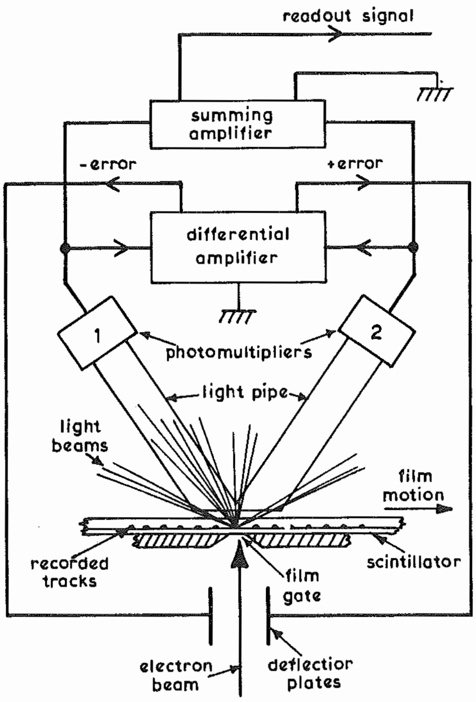

Fig. 5 - Equipment for following tracks recorded on scintillator-coated film

Recordings comprising straight tracks can be followed during replay using a differential technique as depicted in Fig. 5.[30] When the electron beam is centred on the track the light beams scattered into the two symmetrically offset photomultipliers are of equal intensity, and no error signal is fed to the electron-beam deflection circuit. If, however the electron beam wanders towards one side of the track, asymmetric photon scattering occurs, and a correction signal, derived from the difference between the signals from the offset photomultipliers, is fed to the electron-beam deflection circuit. The sensitivity of this servo-control system is not known to the writers, but it might well be adequate for digital television purposes in view of the short transit times and low inertia which are involved.

2.2.3. Electron-beam Recording on Thermoplastic Film

The original idea of thermoplastic film recording[26] involved the scanning of a thin, transparent thermoplastic film with an electron beam of about 10 keV in energy. Data is transferred to the film by modulation of the beam parameters in accordance with the signal to be recorded. The thermoplastic film is usually coated on a relatively thick, transparent, flexible-base film, the two sandwiching a very thin, transparent, electrically-conducting layer, as depicted in Fig. 6(*a*). The charge pattern deposited on the thermoplastic layer by the scanning electron beam can be

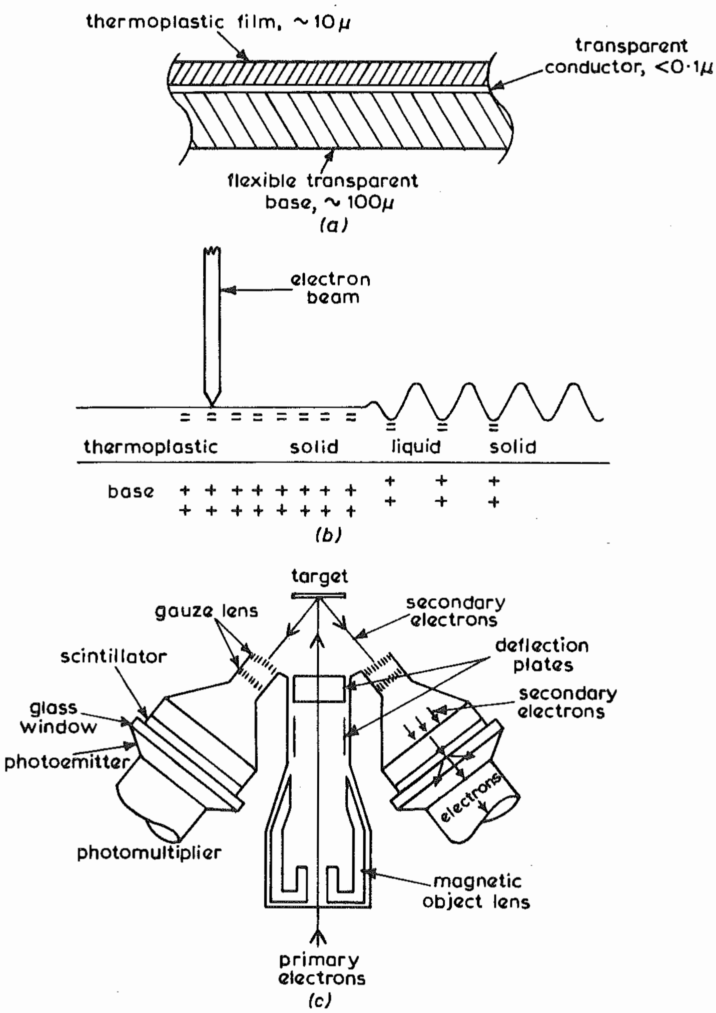

Fig. 6 - Thermoplastic film recording

(*a*) Thermoplastic film
(*b*) Method of data recording on thermoplastic film
(*c*) Replay head for thermoplastic recording

stored temporarily owing to the low electrical conductivity of the layer. The thermoplastic medium is then briefly heated to its softening point (≃85°C), usually by inducing radio-frequency currents in the conducting layer for about 50 milliseconds. At this point, undulations are generated in the thermoplastic surface in accordance with the equilibrium established between surface tension and the electrostatic attraction between the deposited charge and the earthed conducting layer. The film is then cooled, so that the undulations are 'frozen' to form a record of the signal. The sequence of operations is depicted in Fig. 6(*b*). Erasure is carried out by reheating the film to well above the thermoplastic melting point for a relatively long period in order to allow discharging to occur before the layer is solidified. The film can then be re-used.

Recorded bandwidths of some hundreds of megahertz are achieved with this technique,[28] although the signal-to-noise ratio, signal transfer characteristic, error rate, and stability do not match the excellence of the resolution. Also, considerable difficulties are experienced in controlling the physical properties and storage conditions of the film to render it durable under operational conditions and to ensure long life for the recorded undulations.[29] The sensitivity of the medium is low relative to that of photographic film; for similar beam (spot) diameters, beam energies, and scanning rates, the thermoplastic film appears to require about ten times the beam current for adequate exposure.[26,28,30]

Optical projection of an analogue thermoplastic recording requires a phase-contrast projector which can translate the information contained in the transparent undulations of the thermoplastic layer from phase variations to contrast variations in the light transmitted through the film on to a viewing screen.[27] Application of phase-contrast techniques to the replaying of digital thermoplastic recording requires a scanning process so that the digits can be recovered in a convenient serial manner. A conventional flying-spot scanner incorporating phase-contrast optics, although optically very inefficient, could be used up to bandwidths of about 10 MHz. The bandwidth is limited by the scanning-tube phosphor-afterglow time of around 100 nanoseconds and the luminous spot size of around 20 microns.

A more promising technique for wideband digital thermoplastic recording is based upon the collection of the secondary electrons emitted by the film when it is scanned with an electron-beam.[7] The tracks are scanned by a 5 keV primary electron beam which induces the emission of a secondary-electron current comprising a d.c. component and a signal component which varies with the angle of incidence of the primary beam on the recorded tracks. The secondary electron current of the order of a few nanoamperes is collected by two electro-optic heads located in relation to the film as shown in Fig. 6(*c*). In these heads the secondary electrons are accelerated to an energy of about 10 keV, and are then absorbed in a scintillator which emits photons with a quantum efficiency greater than unity. The photons progress to a photomultiplier to yield a low-noise amplified current. Two symmetrical heads are used to facilitate track following in a similar way to that described in Section 2.2.2. However, in this case, the scattered secondary electrons replace the photons scattered from the scintillator coated film. Ageing of the scintillator by electron bombardment is again a problem, but the difficulty is alleviated here by diffusing the accelerated secondary electrons so that they land over a relatively large area of the scintillator. Secondary-electron transit times and scintillator afterglow are of the order of a few nanoseconds so that bandwidths of 100 MHz are attainable. The associated noise performance is not good, and is particularly degraded by the necessary existence of a relatively high d.c. current which is independent of the signal. The degradation is serious in the case of analogue recording, but it should not be as troublesome with digital recordings. A practical 50 MHz analogue system has been demonstrated[7] which used a beam (spot) diameter of about 25 microns and a beam current of 500 nanoamperes. The spot diameter of 25 microns corresponds to a packing density of the order of 2×10^5 bits/sq.cm. The system handled only stationary film, but the servo system was shown to be sufficiently sensitive to accommodate quite severe film transport dynamic errors.

As stated above, detailed specifications for electron-beam recording channels are difficult to find in references now available. The application of electron beams to the recording of digital information appears to have been limited, but no doubt this state of affairs should improve in the not too distant future. It would be quite safe to state that electron-beam techniques could provide ten or more times the data storage capability of conventional recording on magnetic tape.

2.3. Laser-beam Recording

2.3.1. Comparison with Electron-beam Scanning

As an introduction to laser-beam recording, it would be helpful at this stage to compare the laser-beam and electron-beam scanning systems.[25]

Any recording system requires a physical change to be induced in the recording medium and demands a certain amount of energy to bring about this transformation. The speed of the system will be dependent upon the power density at the surface of the medium. Both the electron-beam (just discussed) and the laser-beam are capable of being focused to extremely high power densities. It is possible to obtain about 10^5 watts/cm^2 with an electron-beam, and a typical laser-beam could provide a power density of about 10^7 watts/cm^2. The energy capacity and optical coherence of the laser-beam renders it adaptable to quite novel recording and reproducing techniques discussed below.

The laser-beam can be called upon to perform similar functions to the electron-beam. However, the wavelength of light is much greater than that of the electron and would imply, in theory at least, that the electron-beam should have better resolution capabilities. The information packing density of an electron-beam recording on film is limited by the scattering of electrons upon impact and by the thickness of the recording medium. These effects reduce somewhat the potential packing density of 10^{10} bits/cm^2 which could be achieved with an idealized electron-beam recorder.

The electron-beam spot size is also limited by the beam thermal distribution. In practice, a laser-beam spot size comparable to that effectively provided by the electron-beam can be obtained. Diffraction effects are mainly responsible for the limits imposed upon information packing density and frequency bandwidth obtainable with a coherent light recording/reproducing system.[25,31] There are diffraction limits associated with the laser itself and subsequent aperture-limited focusing optics. Reproducing limits are given by the Fraunhofer diffraction pattern scattered from the recorded information bits, as well as the diffraction limits of the reproducing optics.

Lasers do not require a vacuum for satisfactory operation, thus offering quite a significant practical advantage over the electron-beam recorder. This immediate benefit is somewhat offset by the difficulties encountered in the deflection and modulation of a laser-beam. In order to accommodate the relatively large format encountered in digital data recording systems, some form of mechanical scanning is usually adopted for the laser-beam. One system uses the movement of the recording medium and a rotating mirror to generate a helican scan.[32] Optical deflection techniques involving physical rotation usually demand very tight tolerances and the use of specialized materials, thus making them expensive relative to electron-beam deflection. However, mechano-optical systems are inherently linear and possess an inertia which, when coupled with high-precision mechanics, can produce a very stable scan uniformity. This factor makes a substantial contribution to the information packing density which can be achieved with a laser-beam recorder. The electron-beam is very sensitive to the stray magnetic and electric fields which may be present in its environment. Further, the electron-beam deflection system has very little inherent inertia, and therefore requires very tight servo-control for accurate tracking in both the recording and reproducing modes. However, owing to this low inertia, the electron-beam can be easily applied to any non-linear scanning configuration.

The remaining topic to be discussed in connection with scanning systems is the modulation of the writing beam by the digital information to be recorded. Extremely high scan velocities can be achieved with both the electron-beam and the laser-beam, and consequently (ignoring for the moment the characteristics of the recording medium itself) modulation techniques become very important when considering the linear resolution attainable on the medium. (The bandwidth of the recording system is equal to the product of the scan velocity and linear resolution.) Intensity modulation of the electron-beam is now a well established art, and can be used in all existing electron-beam recorders. A relatively cheap, reliable, very wide-band modulator is needed to take full advantage of laser-beam properties outlined above. Modulators have been produced (and are briefly described below) which render the laser-beam recorder capable of providing a higher resolution than that obtainable with the electron-beam recorder.[33,34]

The modulation of a laser-beam is effected by inserting an electro-optic element in the path of a linearly polarized beam in order to rotate its plane of polarization. The amount of rotation is a function of the magnitude of the signal voltage applied to the modulator. The polarization modulation is then converted into intensity modulation by a polarization analyser attached to the modulator.

The Kerr electro-optic effect has long been associated with devices used experimentally as 'light-choppers'. The active element is usually a liquid dielectric (e.g. pure nitrobenzene) which, when placed in an electric field, behaves optically like a uniaxial crystal with the optic axis parallel* to the field direction. The Kerr cell can rotate the plane of polarization of a light beam incident upon the cell from a direction perpendicular to the applied field. The Kerr-cell modulator can be switched at radio-frequencies but has disadvantages: it is relatively insensitive and the liquid dielectric has toxic properties.

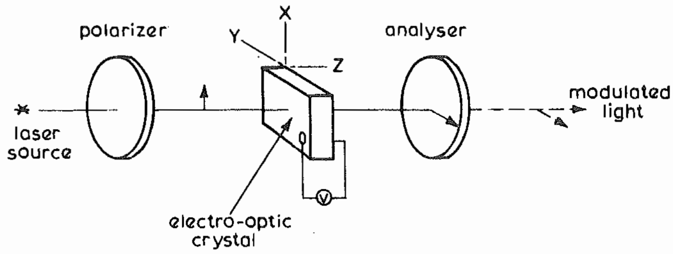

Fig. 7 - The electro-optic modulator

A more recent development has been a modulator whose operation depends upon the Pockels effect. This is similar to the Kerr effect but the transparent dielectric now assumes the form of a piezoelectric crystal, and the electric field is applied parallel to the crystal optical axis in the same direction as the incident light (referred to as a longitudinal modulator). The Pockels cell has five to ten times the sensitivity of the Kerr cell, and in one application[33] the contrast ratio of the modulator exceeds 100 to 1 for a change in signal of 210 volts. Pockels' electro-optical effect is also a linear function of the applied electric field, whereas the transfer function of the Kerr-cell modulator depends upon the square of the applied field. The Pockels cell (discussed in outline below) is also reliable, relatively cheap, and can modulate a laser-beam from d.c. to more than 30 GHz. Collimated light from the laser is passed through an input polarizer which produces a linearly-polarized beam of light (Fig. 7). The input polarizer has its direction of polarization parallel to, say, the X-axis of the crystal. The analyser (output polarizer) has its direction of polarization at 90° to the input, along the Y-axis in this case. A transmission minimum exists when there is no voltage applied to the crystal. As the voltage across the crystal is increased, the light transmitted also increases. Maximum transmission is reached when the plane of polarization of the beam has been rotated by 90° while passing through the crystal, and therefore coincides with the orientation of the analyser.

The Pockels cell is now widely used as the modulator for both analogue and digital laser-beam recording systems.

* The direction of the incident light beam is perpendicular to the optic axis.

The principal difficulty encountered in the electro-optic modulators now available is the provision of sufficient signal voltage to achieve an adequate contrast ratio. The lowest range of operating voltages is given by using a crystal of potassium dideuterium phosphate as the dielectric element; however, wide-band pulse signals of the order of 1000 volts peak-to-peak may be necessary for digital recording on media other than silver-halide film, requiring a special power amplifier.

In order to reproduce laser recorded signals the medium carrying the information is replaced into the equipment used for the recording and is scanned by a laser-beam of reduced power. This laser-beam, operating in the reading mode, has a constant intensity with the modulator de-activated. The beam is intensity modulated by the bits of information recorded on the medium and is collected by an optical system which directs the energy on to a photodetector. The photodetector produces the required electrical output.

2.3.2. Laser-beam Recording on Photographic Film

Silver-halide film is one obvious possible information-storage medium for a laser-beam recorder. The parameters affecting the bandwidth attainable with these recorders will therefore be discussed and a recent machine described.[33]

The high resolution and scan stability provided by the laser-beam make the silver-halide film itself one of the principal causes of the limitations in bandwidth obtainable. It is essential to use the finest-grained silver-halide films in order to achieve a maximum signal-to-noise ratio for the signals recovered from the film. These high-definition emulsions have a low exposure sensitivity, but fortunately the laser can offset this by providing the high power necessary when recording at high scanning rates. As stated earlier, diffraction effects limit the size of the laser spot to a diameter dependent upon the operating wavelength (e.g. spot-size of 0·37 microns with an f/1 lens at 3000 Å); also, the effective diameter is limited still further by photon scattering and film granularity. However, diffraction-limited spot sizes of 0·5 microns can be obtained, and further improvements in the film emulsion could justify this order of resolution. Owing to the large inertia of the laser-beam scanning system, the time-base errors are not a function of the scan rate, and an accuracy of 0·1 ns is possible. The packing density is again limited by the storage medium, but a track width of 2·5 microns and track separation of 7·5 microns should become feasible in the future. The signal-to-noise ratio of the output signal is governed by the power of the laser used in the reading mode. A focused power density of 10^7 watts/cm^2 could give an output signal with 40 dB signal-to-noise ratio.

The factors outlined above, coupled with a suitable recording format, suggest that bandwidths of 1000 MHz could be secured as a result of further developments in this field. When applied to digital signals, the data transfer rate of a recorder using a laser of given power will depend upon the signal-to-noise ratio that the system as a whole could tolerate.

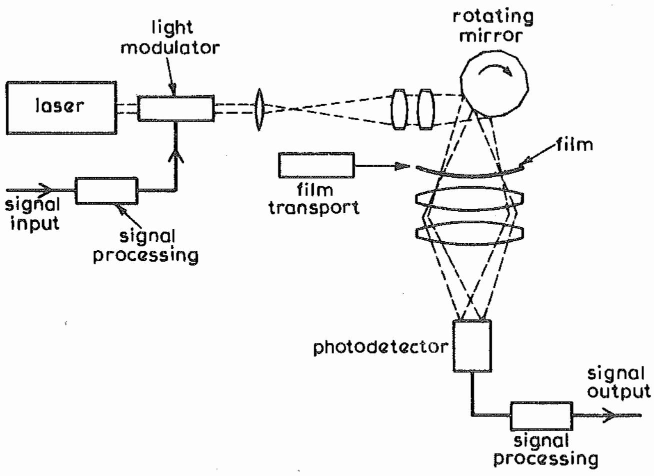

Fig. 8 - Laser signal recorder components for recording and reproducing signals with silver-halide film

A simplified diagram of a 100 MHz laser signal recorder is shown in Fig. 8. As with all laser recorders great care is taken to ensure that the film moves in the precisely defined focal plane of the laser-beam, and a curved film transport table is used for this purpose. The transverse scan is generated by an 18-faced beryllium polygon mirror (rotating at 133,000 revolutions per minute), and provides continuous recording of the signal information. A 100-milliwatt argon laser is used in the recorder which, because of the relatively short wavelength, helps to reduce the size of the recording spot (10 microns) with a consequent reduction in the modulating power required. The separation between the recorded tracks is 38 microns. The film used is 70 mm wide, and a scan line can therefore be 50 mm long. It is possible to resolve 5000 elements on each scan line; as the line scan rate is 40,000 scans per second, the recorder provides a bandwidth of 100 MHz. The recorder accommodates 915 metres of film and this is transported across the focal plane of the laser-beam at 1·53 metres per second. The total recording time is therefore 10 minutes.

2.3.3. Laser-punched Tape

The high power-density provided by the laser-beam can be used to record digital information by punching diffraction-limited holes in the surface of a recording medium which has been specially developed for this application.[32] In binary notation the presence of a hole would represent 1, and the absence of a hole would signify a 0. This technique offers distinct advantages over all the recording systems which have been previously considered in this report; production models should be available fairly soon.

The recording medium consists of a transparent polyester backing film which carries an opaque surface coating having a thickness of 4 microns. As in the silver-halide recorder, this film has to be precisely located in the focal-plane of the modulated laser-beam. The focus of a diffraction-limited laser-beam assumes the form of an ellipsoid of revolution. The focusing optics have to be so matched to the recording medium that the length of the major axis of the ellipsoid is equal to the thickness of the opaque layer on the film; vaporization of the coating can then be effected without damaging the polyester base.

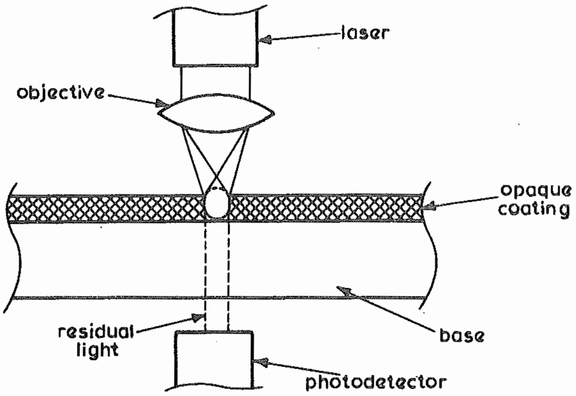

Fig. 9 - Laser-punched tape recorder: location of vaporized hole in tape

The configuration of a data hole in the medium is shown in Fig. 9. During this vaporization process the temperature of the laser image is 30000°K, and the vapour pressure inside the volume occupied by one bit on the tape reaches 1000 atmospheres. A continuous-wave argon laser has been used in these recorders with a maximum power over all its modes of one watt. The wavelength of 4880 Å carries the maximum intensity of 0·45 watt, and is separated from the rest of the laser output by means of multiple-layer dielectric filtering. The diameter of the holes produced is 1·5 microns, and the spacing between the recorded bits is approximately 3 microns. (Experimental recording of 0·7 micron holes has been accomplished.) After vaporization has occurred, the optical density of the surface layer is practically reduced to zero, and the power of the laser-beam which is transmitted through the bit area is increased by 70 dB. The one great advantage of this type of recording is that, by monitoring the writing laser-beam after its interaction with the recording film, recorded information can be checked immediately against input data; the error rate is only one bit in 10^9 over the whole recording, storage, and readout process. It is not yet clear how this error rate varies with data transfer rate. Further, as this is not a photographic technique, troublesome medium processing requirements are avoided. The information packing density obtainable with this recorder is about 10^8 bits per square centimetre. This laser recorder has 1000 times the volume storage capacity of magnetic tape. The data storage capacity provided by a continuous tape-transport system would appear to be the most suitable for recording digital television signals. This will now be described, and is illustrated in Fig. 10.

The original prototype machine used 16 mm film, but data access time could be reduced if 35 mm film was used; proposed system parameters will therefore be quoted for 35 mm film. The point in space where vaporization must take place is well defined by the imaging circle of the laser aperture, this being formed by the diffraction-limited objectives rotating at 1800 revolutions per minute. The polyester tape is moved slowly (about 1 centimetre per second) by a helical-scan transport around the surface described by this circle, and the two diametrically opposite objectives allow continuous recording and readout to take place. The recorded tracks are therefore inclined to the tape transport direction; the inclination would be 1°43′ for

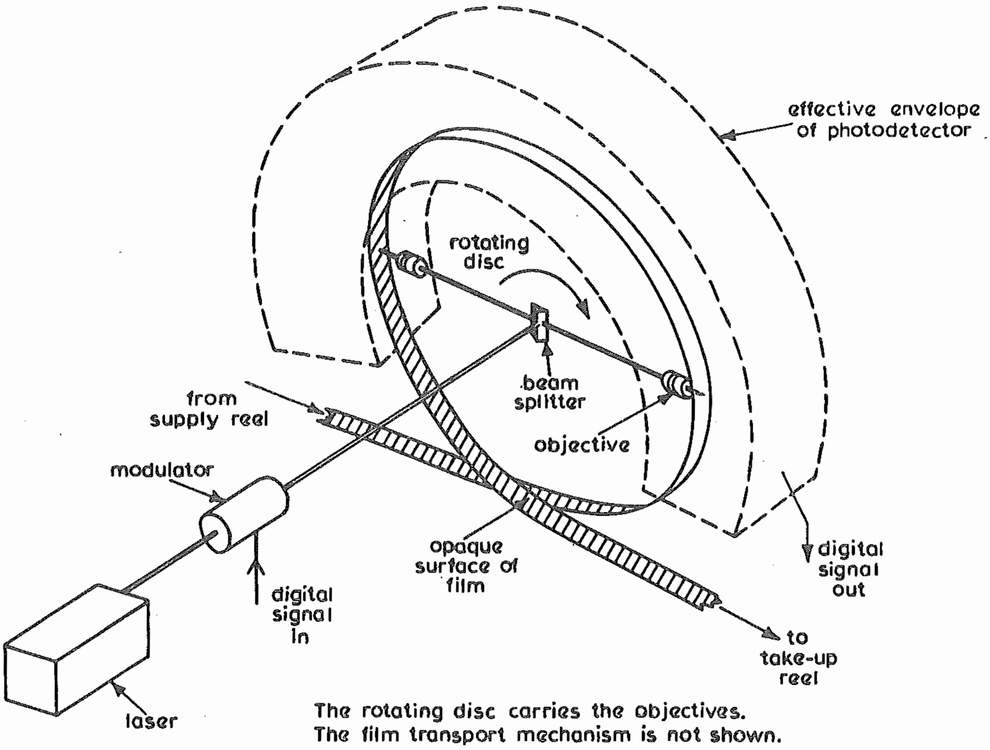

Fig. 10 - Helical scanning system for the laser-punched tape recorder

35 mm film. The layout of recorded tracks is illustrated in Fig. 11. A track 30 mm wide would be available for recording input data, with a 4 mm border reserved at one edge of the tape for a binary track indexing system. The other edge of the tape would carry a 1 mm border for storage of timing (clock-pulse) information. The recorded tracks would be 1 metre in length and each could be capable of storing 10^6 bits of information. Track separation normal to the direction of recording would be 4 microns, and owing to the angle of incidence, the separation between the tracks along the length of the tape would be 167 microns, thus providing a track density of 60 tracks/cm.

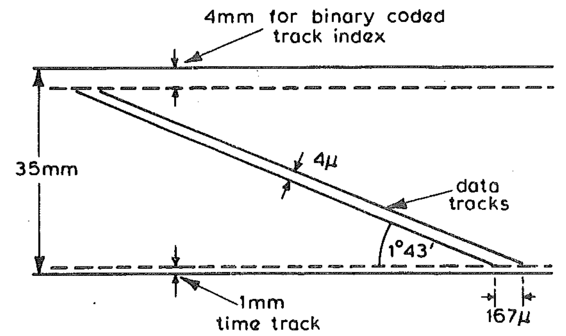

Fig. 11 - Data track layout for the laser-punched tape recorder

When reading, the power of the laser is reduced to 3 per cent of that required for recording. This avoids any alteration to the opaque coating on the tape. The light transmitted through the film is monitored for checking and for subsequent readout of the information. A plexiglass light guide completely surrounds the imaging circle of the laser aperture and directs the transmitted light to a central photomultiplier.

A laser-punched tape recording system using these essential principles could now achieve a data transfer rate up to 20 megabits per second. Additional development work would be required to achieve the 100 megabits per second required for the recording of digital television signals.

Compact and permanent storage of recorded material presents no problems. The quality of the recording should not deteriorate with time, and readout could be carried out 10,000 times before drop-outs appear. One disadvantage is that the recorded information cannot be erased from the tape. However, this technique appears to have great potential for the storage of large quantities of data at very high transfer rates.

2.3.4. Photochromic Recording

Photochromic materials exhibit a reversible change in their absorption spectrum when irradiated with light of an appropriate wavelength. Data recording can be achieved by the generation and detection of these changes.[8,35]

Many chemical compounds are photochromic. The atoms or molecules of these compounds can be switched between two distinct states when bombarded with photons from a suitable source of light (usually in the ultra-violet region of the electromagnetic spectrum). These transitions represent alterations in electronic orbital structure and give rise to the spectral shift mentioned above. The compound will return to its 'ground-state' and assume its initial spectral properties when the activating radiation is removed. These excursions can be regarded as elements of a thermal process; before reversion to the initial state can take place a thermal energy barrier has to be overcome. Photochromic behaviour therefore depends upon temperature. An increase in operating temperature would reduce both the maximum change in optical density of the photochromic film and also its lifetime in the state before reversion takes place. By working at sufficiently low temperatures the thermal reversal can be suppressed by trapping the atoms and molecules in the excited condition. However, this temperature dependence does represent a major disadvantage of this medium for long term data storage at present.

The photons porvided by the irradiating source must be absorbed by the photochromic film, and must have sufficient energy to effect the transformation. The wavelength of the writing laser-beam is therefore determined by the absorption spectrum of the film before activation, and Fig. 12 is typical of the changes that would take place in a blue-sensitive type of photochromic medium: writing would take place at 4800 Å resulting in a modified absorption spectrum with a peak at 6000 Å. The readout of information would therefore be carried out at a wavelength of 6000 Å where the maximum change in optical density occurs. For erasing, temperature of the film must be increased. In one experimental recorder controlled erasure is performed by using a laser-beam operating in the infra-red region of the spectrum.

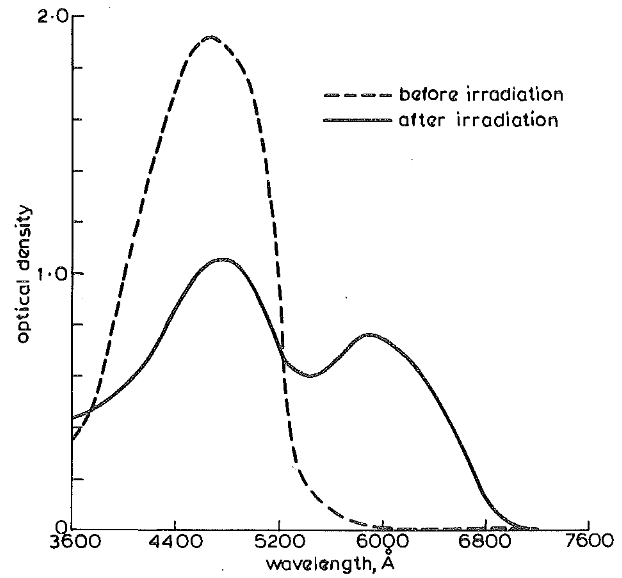

Fig. 12 - Absorption spectra of blue-sensitive type of photochromic film

The information packing density of a photochromic medium is very high because the physical transformations in the film occur on a molecular scale. There are therefore no restrictions imposed on the storage density by 'grain' as in the silver-halide recorder. On this basis, the idealized

packing density for a photochromic recorder could be extremely high, but practical considerations such as the finite spot size of the laser-beam, halation in the photochromic medium coupled with tracking difficulties reduce this figure to around 10^6 bits per square centimetre. Photochromic materials have a very fast inherent switching speed. The molecules can assume their modified electronic configurations in times between 10^{-13}s and 10^{-7}s, and would therefore allow data transfer at 10^8 bits per second; the cost per bit could be extremely low. The medium does not require processing and could be used for many write-erase-rewrite cycles. The readout process is, in principle, non-destructive.

The details given above compare favourably with the corresponding parameters of other recording systems, but the long term storage stability of this medium would have to be improved before it could be seriously considered as part of a viable recording unit.

2.3.5. Thermo-magnetic Recording with Magneto-optic Replaying

The storage medium used in this type of recorder is a magneto-optic compound whose magnetization has two stable directions perpendicular to the plane of the substrate which supports it. These two directions can represent the 1 and the 0 of a binary coded signal and a magneto-optic effect is used to discriminate between them. The Kerr magneto-optic effect is observed as the rotation of the plane of polarization in a beam of light when it is reflected from a magnetized surface (the pole of an electro-magnet for example). Several solids, liquids, and gasses exhibit the Faraday magneto-optic effect when they are subjected to a strong magnetic field. In this case, the plane-polarized light is transmitted through the medium in a direction parallel to that of the applied magnetic field and again, a rotation in the plane of polarization is detectable. The Faraday effect appears to be the one incorporated in the more recent developments of this type of recorder, and this configuration is illustrated in Fig. 13.[9,36,37,38,39]

The resolution, optical-coherence, and power density of the laser-beam again make it the obvious choice for generating and detecting the physical changes in the magneto-optic medium. Various types of garnet were amongst the first compounds to be developed for this technique, but quite recently an improved bandwidth, information packing density, and signal-to-noise ratio have been achieved with a compound of manganese and bismuth; the parameters for this medium will therefore be quoted here.

Initially the film memory is magnetized perpendicular to its surface in one direction only, and therefore carries no information. Writing is effected by applying a collinear magnetic field of opposite polarity, and simultaneously heating the addressed bit with a high-intensity laser-beam when, say, the binary 1 is to be recorded.[6] Magnetization reversal can be carried out by heating the appropriate point of the film to its Curie-point (360°C). The medium then loses its ferromagnetic properties, and upon removal of the beam it will cool down and assume the orientation of the externally applied magnetic field. Theoretically, the packing density would be limited by the minimum magnetic domain size which lies between one half and one micron. However, owing to diffraction-limited optics and the interaction between adjacent bits produced by heat diffusion in the medium, an effective spot diameter of 3 microns appears to be more realistic. It is proposed to evaporate the manganese-bismuth film on to the substrate into discrete 3 micron spots, this would minimize thermal interaction and also the magnetic effect of unused background material; accuracy during readout would also be improved. A spot separation of 10 microns would ensure a packing density of 10^6 bits/cm^2.

The writing rate is obviously dependent upon the power of the laser-beam; a one microsecond pulse from a 2·2 milliwatt laser has been found capable of raising the bit temperature on this medium from 0°C to 360°C. A uniform temperature throughout the bit volume is achieved by using films of the order of 1000 Å in thickness.

A linearly-polarized, unmodulated laser-beam of reduced power is used for reading, and strikes the magnetic pattern recorded on the magneto-optic film at normal incidence. The plane of polarization will be rotated in one sense for a zero-state, and in the opposite sense for a one-state. The alignment of the polarization analyser can be adjusted to extinguish the beam in the zero-state. The photodetector then provides the required electrical output from the intensity modulated beam.

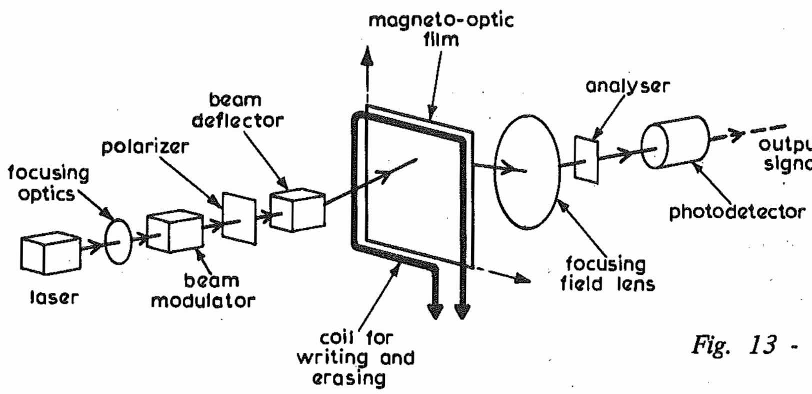

Fig. 13 - Components of the thermo-magnetic/magneto-optic recorder

The absorption and magneto-optic characteristics of a given compound both depend upon the wavelength of the incident radiation. The radiation must be absorbed by the medium for efficient recording to take place, and, secondly, the wavelength should be associated with a large magneto-optic effect for maximum signal-to-noise ratio in the whole system. The rotation of the plane of polarization, (θ), is given by the following equation:

θ = Verdet constant x magnetization x thickness of film

The Verdet constant is defined as the rotation per unit path length per unit field strength. If the absorption of the medium is denoted by α, a factor $2F/\alpha$ (where F = Verdet constant x magnetization) is used to determine the optimum operating wavelength. As pointed out above, $2F/\alpha$ should be large for a good signal-to-noise ratio in the readout signal, whereas α should be large for efficient recording. Fortunately a compound of manganese and bismuth has a very large value of F, sufficient in fact to sustain its high absorption, α, at an operating wavelength of 6328 Å provided by a helium-neon laser. A manganese-bismuth film which is 1000 Å thick will absorb 95% of the energy in a 6328 Å laser-beam. It is claimed that no other material now known will satisfy to the same extent these exacting requirements (apart from materials which require cryogenic cooling).

The following performance figures expected from an actual optical memory have been quoted by the developers of this system:

Bit density on storage plane	10^6 bits/cm^2
Required laser power for writing (He-Ne at 6328 Å)	10 milliwatts
Writing speed	10^6 bit/s
Reading speed	10^8 bit/s
Orientation field for writing	10 oersteds

Complete erasure of the stored information is effected by the application of a magnetic field of 3500 oersteds for 20 μs. The recording medium can be used at room temperature, but can also function satisfactorily between −100°C and 300°C.

Digital television signals would require a higher writing speed, but perhaps future developments with more powerful lasers would permit both writing and reading data transfer rates of 10^8 bits per second.

2.4. Electron-beam Recording with Laser-beam Replaying Using Optical Spatial Filtering

In the very high density recording systems hitherto discussed, the prevalence of 'drop-outs' when reading recorded information may become unacceptable, particularly after a period of storage or several replay cycles. This could be avoided by careful handling of the recording medium. With silver-halide film for example, a slight scratch or particles of dust and dirt over a very small area of the film could obliterate the recorded information. The system now discussed distributes the information carried by one bit over a larger area of film and therefore acquires a greater degree of protection from surface irregularities on the medium. Information corresponding to 8 bits can also be superimposed over a given area of the film and therefore the decrease in packing density is less then would otherwise have to be made. The increase in area of the recorded bit also helps in the location of a recorded character on the film.[40,41]

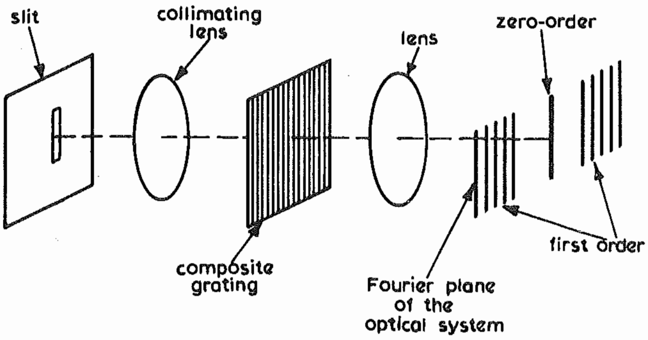

Fig. 14 - The basic optical system producing a number of first-order lines from a composite diffraction grating

With this method of recording, each bit of a character or word is represented on the film by an image of a diffraction grating of a particular spatial frequency. If eight bits per character are to be recorded then eight individual diffraction gratings have to be superimposed at a given point on the film. Each character could represent the magnitude of a sample of the television waveform coded into eight binary digits. In order to recover information from the photographic emulsion, the composite grating formed from the eight linearly-spaced gratings is illuminated with monochromatic light. The Fraunhofer diffraction pattern observed in the Fourier plane of the reading optical system will contain a pair of first-order lines for each spatial frequency in the composite grating; this is illustrated in Fig. 14. By using spatial filtering techniques, a photodetector can be made to monitor each first-order line. The presence or absence of each of these lines gives a direct indication of those diffraction gratings which were present in the original recording. The parallel outputs from the photodetectors would then represent the binary information, and, if necessary, could be fed directly to a digital-to-analogue converter for recovery of the original television waveform. If the recorded grating patterns do not have a purely sinusoidal amplitude characteristic, some confusion due to the presence of second-order lines could arise in the Fourier plane. This interference can be avoided by restricting the range of grating spatial-frequencies to within an octave. The first-order lines of interest will then lie between the first-order and second-order lines formed by the component of the composite grating having the lowest spatial frequency. The zero-order line will have the greatest intensity, but a viable experimental system in which seven grating patterns were superimposed obtained first-order lines as strong as 10% of the zero-order line.

The recording techniques that so far appear to have been developed for this type of recorder have data transfer

rates quite inadequate for digital television. One of these methods generates the diffraction gratings by suitable modulation of the display on a cathode-ray tube. This display is focused on to a high resolution emulsion by a high quality optical system. The electron-beam scanning system in the tube is gated to a number of oscillators in turn, there being one oscillator for each digit in a character. The frequencies of the oscillators determine the spatial frequency of the recorded grating. One experimental machine using this method has recorded seven binary digits in one photographic character, at character rates of up to 15 kHz. This corresponds to a data transfer rate of $1{\cdot}05 \times 10^5$ bits per second and the associated packing density was $7{\cdot}7 \times 10^4$ bits/cm^2. By using direct electron-beam recording techniques outlined above, it should be possible to increase the writing speed, but no information appears yet to be available on such a system.

For readout purposes, a cylindrical lens configuration is used to form a line image of the laser beam at right angles to the grating pattern recorded on the film. This ensures that almost all the laser output is concentrated into the grating pattern. Helium-neon lasers with a nominal output of 1 mW have been used experimentally. The first-order patterns generated had sufficient intensity for them to be read with simple photo-diodes at a rate of 10^5 characters per second, a data-rate of 0·7 megabits per second. Detailed studies of error rates have not yet been carried out. By using simple circuits such as Schmitt triggers and coincidence gates, uniform output pulses free from noise have been obtained for character dimensions of 7·5 microns x 500 microns. Seven bits per character have been recorded with characters spaced on 15 micron centres, this corresponds to a packing density of $9{\cdot}2 \times 10^4$ bits/cm^2.

The recordings cannot be erased, and the medium requires processing before readout can take place. However, the error protection inherent in this system provides obvious advantages, and the application of more sophisticated reading and writing techniques may increase the data transfer rates to limits acceptable for digital television recording.

3. A COMPARISON OF DIGITAL RECORDING TECHNIQUES POTENTIALLY SUITABLE FOR TELEVISION

Recording and replaying speeds will be considered separately because in some cases the physical processes involved in the reading and writing operations are quite different and they place their own limitations on the data transfer rates attainable in each case.

The summary chart enables direct comparisons to be made between selected parameters of the recording systems outlined in this report. It must be emphazized that this chart cannot be used as a direct guide to the recording technique most suitable for digital television purposes. The operational utility of each system requires very careful consideration.

3.1. Recording Speeds

The developments in static-heads longitudinal magnetic recording have reached the stage where it should be possible to record and replay data at 70 megabits per second. The development figure quoted earlier in this report would suggest that a further increase to a full television data rate of 10^8 bits per second would be possible. Previous remarks also indicate that a transverse-scan recorder could be adapted to handle data transfer rates of 10^8 bits per second.

The maximum data transfer rate for a single track on a magnetic (disc) recorder appears now to be 3 megabits per second. Future development work with metal-coated discs using 'in contact' heads should increase this data-rate to 10 megabits per second. However, by simultaneous use of all the recording heads available on some current disc recorders, a data rate of 10^8 bits per second is possible. A single disc store is available with two recording surfaces and thirty-six read/write heads per surface. Each head is capable of handling 3 megabits per second and therefore the total parallel data-rate is $2{\cdot}16 \times 10^8$ bits per second. A drum store, available commercially, has 800 read/write heads on its circumference, each with a possible data-rate of 2·5 megabits per second. In this case the parallel data-rate could be 2×10^9 bits per second. As designed, many of these recorders have only one effective channel operating at a given time, and to adapt them for a parallel working would require complex multiplexing of the data channels. Their total storage capacity would only allow them to operate as buffer stores.

For electron-beam and laser-beam recorders there is in most cases a potential recording bandwidth in excess of 100 MHz, but practical considerations will limit the bandwidth that is finally realized. Operational factors will also determine their suitability for digital television recording. Many of these techniques are still in the experimental stage of their development, and the application to digital recording has been somewhat limited. The electron-beam in association with silver-halide and thermoplastic film can achieve bandwidths in excess of 100 MHz, and a laser-beam/silver-halide film recorder having this bandwidth has already been demonstrated. Optimistic writing speeds for the superposed-grating recorder (using the direct electron-beam) and the thermo-magnetic recorder would appear to be 10 megabits per second. The laser-punched tape recorder will achieve recording bit-rates of 20 megabits per second, and its extension to the demands of digital television is possible.

3.2. Replaying Speeds

The readout of information from a high-density storage medium requires very careful control of the track following mechanism, but once this problem has been overcome some of the very sensitive physical processes involved give rise to very high data transfer rates.

The replaying and recording speeds of the conventional magnetic recorders given as examples in the previous section are identical.

A replaying bandwidth of 10 MHz has been achieved with the electron-beam/silver-halide film recorder. The afterglow of the scintillator-coated film should not restrict an approach to a data-rate of 10^8 bits per second, and future developments could realize this target. The fastest method of replaying a thermoplastic recording is to collect the secondary electrons scattered from the film. A replay bandwidth of 50 MHz has already been developed using this technique and an increase to 100 MHz would appear to be quite feasible. The laser-beam/silver-halide film recorder has already appeared with a 100 MHz replay channel.

The developers of the laser-punched tape recorder claim that they should be able to read and write at 20 megabits per second. Considerable research effort would be required to achieve a data transfer rate of 10^8 bits per second.

The proposed readout rate for the magneto-optic medium is 10^8 bits per second, also capable of being matched in the future by the spatial-filtering techniques of the grating-pattern recorder.

3.3. Error Rates

The high density digital recording techniques described above are being designed to handle the large volumes of data which will be generated by the huge computer networks of the future. The accuracy of the writing and reading functions of these machines must therefore be compatible with the high standards provided by the computers themselves. It is doubtful whether a digital television system will demand this 'computer accuracy'; future experimental work could establish the tolerance in error rates by subjective experiments on the re-constituted television display. However, it must be remembered that the broadcasting authority provides the primary source of television signal, and the degradation at each interface in the whole system must be minimized.

The longitudinal magnetic recorder will provide an accuracy of 1 bit in 10^7 at its maximum linear packing density of 400 bits per millimetre. A transverse-scan machine is capable of achieving an error rate of 1 bit in 10^9. The magnetic disc and magnetic drum again provide a reliability in the range of 1 bit in 10^7 to 1 bit in 10^9, and the use of suitable error-correcting codes could even improve these figures.

At present, information on electron-beam machines applied to digital recording is somewhat limited, but the laser-beam/silver-halide recorder has provided a 40 dB signal-to-noise ratio in its readout signal. The laser-punched tape machine has a specified accuracy of 1 bit in 10^9 for recorders already developed to production standards.

The thermo-magnetic/magneto-optic recorder is still in the early stages of its development and reliable information on its future accuracy does not appear to be available, although the error rate of the superposed grating recorder has been forecast to be between 1 bit in 10^7 and 1 bit in 10^9.

It seems unlikely that error rates of digital recording machines will provide obstacles to the designer of a digital television system.

3.4. Information Packing Densities

The maximum practicable packing density of the longitudinal magnetic recorder is given as $1{\cdot}6 \times 10^5$ bits/sq.cm., with a tape speed of 3 metres per second to accommodate the data transfer rate of 10^8 bits per second. One hour of programme material would therefore require 10,800 metres of tape. This packing density may be increased by future improvements in the tape coating.

Magnetic disc and drum recorders which are capable of a parallel data-rate approaching 10^8 bits per second are now commerically available. Consider two such exchangeable-disc stores with flying heads. One incorporates 10 recording surfaces with 1 read/write head per surface and has a total storage capacity of $4{\cdot}8 \times 10^7$ bits; this is equivalent to 24 television fields (on the 625-line, 50 fields per second standard). The other carries 12 recording surfaces with 12 read/write heads per surface; each track holds 4×10^4 bits and has a total capacity of $7{\cdot}5 \times 10^7$ bits which is equivalent to about 36 television fields. The fixed-disc store will carry more information because of its larger size, and one such machine with flying heads and 50 recording surfaces carries 5×10^4 bits per track with a total storage of 4×10^9 bits. This recorder would therefore carry approximately 1800 television fields. The 5×10^5 bits/sq.cm. which may be provided by in-contact heads with a projected $2{\cdot}5 \times 10^5$ bits per track could provide storage of 2×10^9 bits (800 television fields) on a multi-disc machine. A magnetic drum store in use with present day computers could store 17 television fields.

Fortunately a marked improvement is encountered with electron-beam and laser-beam recorders. The electron-beam and laser-beam/silver-halide recorders already developed are capable of storing $1{\cdot}55 \times 10^5$ bits/sq.cm. and have a potential of increasing this figure to $3{\cdot}1 \times 10^6$ bits/sq.cm. The laser-punched tape recorder can provide a phenomenal 10^8 bits/sq.cm. The photochromic method can maintain 10^6 bits/sq.cm. as could the thermo-magnetic/magneto-optic recorder, but the latter is stated to have a potential packing density of $1{\cdot}55 \times 10^7$ bits/sq.cm. The present-day packing density of an experimental superposed-grating recorder is $9{\cdot}2 \times 10^4$ bits/sq.cm. with a potential of $3{\cdot}1 \times 10^6$ bits/sq.cm.

By using the electron-beam and laser-beam recorders, one hour of programme material could be stored on less than 90 metres of film.

3.5. Operational Utility

Many factors contribute to the operational utility of a recording system. The magnetic recorder is well established in the field of broadcasting, and the only problem likely to be encountered in its adoption to digital television applications may be the volume and cost of the magnetic tape required to store programme-length material.

Vacuum pumping equipment would be required for the electron-beam recorder, although evacuation cycling times of 30 seconds have been achieved with some machines. The laser-beam devices obviate this problem, but adequate protection from the beam itself would be necessary. The total power requirements of the two systems would have to be compared.

The silver-halide film cannot be erased and requires processing before readout can take place. The advent of dry processing techniques with a processing time of around 30 seconds would help to eliminate this discontinuity between record and replay.

Thermoplastic media require no processing, but problems of r.f. heating and subsequent cooling under carefully controlled conditions arise. There is a degradation in the performance of the film after successive write/erase cycles have taken place.

Thermo-magnetic writing requires careful control of the laser power, as opposed to the punched tape systems where the tolerances are not quite so critical.

The photochromic media are not stable enough to be considered for long-term storage purposes.

These brief notes give some indication of the problems to be faced in the future. The cost of the storage medium, its handling and storage have all to be considered, and no firm conclusions on these points can be made at the moment. It would seem that the operational requirements of these novel recording systems are going to pose some very interesting problems should their future adoption take place.

4. CONCLUSIONS AND RECOMMENDATIONS

Magnetic tape recording using the usual electromagnetic head techniques would provide a useful basis for the experimental recording of digital television signals, even though the full data rate of 10^8 bits per second may not be achieved in the first instance. Magnetic discs and drums are potentially useful as buffer stores provided that they are operated on a multichannel basis. Electron-beam techniques, especially on photographic film, offer considerable promise even though inconvenient technicalities such as high vacua and film processing are involved. A marked advantage here lies in the relatively low cost of silver-halide film as the recording medium. The additional inconvenience and expense of thermoplastic recording makes it an unattractive proposition in this context. Of all the laser-beam recording techniques described above, the system using laser-punched tape appears to be the most appropriate. The kinship between the 'hole or no hole' nature of the recording and the 'one or zero' nature of the digitized information offers a clear and compelling indication of its suitability. One of the major drawbacks of this technique may be cost, both capital and running. A second drawback lies in the precautions to be taken to ensure the safe operation of a high power c.w. laser.

This survey is essentially a 'state of the art' report, although some attempt has been made to predict future performance figures of the various recording systems considered. A careful watch should be maintained on future developments, and it is expected that a high density recorder with a data transfer rate of 10^8 bits per second suitable for recording programme material may be available within five years.

It would seem that the requirements of digital television are going to place heavy demands upon any recording system used for its long term storage. When future consideration is given to the overall system design it would be worth questioning whether a data rate of 10^8 bits per second for television is really necessary. It has been assumed in this report that the absolute sample amplitude has to be coded into eight binary digits; a differential pulse-code modulation system which recognizes the difference in amplitude between successive samples may represent a more efficient encoding process.

5. ACKNOWLEDGEMENTS

While collating information, as part of this feasibility study, a number of contacts were made with representatives and research workers in industries concerned with the manufacture of digital recording equipment. Our thanks are due to them for their willingness to provide details of their work.

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Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey